INTERNATIONAL FRESH PRODUCE ASSOCIATION

Occurrence of plastic micro- and nano-particles in the specialty crop production: State of the Science review

Key Takeaways:

- While micro and nanoplastics are ubiquitous in the environment, health agencies worldwide do not link their presence in the environment with a risk to human health
- Micro and nanoplastics are often found in shellfish and other seafoods
- In the US, major sources of microplastics in the production environment (biosolids, urban run-off, heavily contaminated surface waters) are already excluded from fruit and vegetable production for FSMA compliance
- The majority of reports of microplastics in crop production environment are from Asian countries where overall environmental contamination with plastic waste is alarming. Results of these surveys should not be extrapolated to other regions.
- Even when present in soils, most microplastics are not taken up by plants. Some nanoplastics that can be taken up by plants were derived from materials like Styrofoam, which is already being phased out.

Executive Summary. Microplastics (MPs) and nanoplastics (NPs) are ubiquitous in the environment and this presence in the environment and in certain foods increasingly draws attention from consumers and regulators. Public health agencies like the US FDA, Health Canada, and the WHO acknowledge the presence of MPs and NPs in the food supply but emphasize that current scientific evidence does not conclusively show a risk to human health. In the United States, the only direct legislation targeting microplastics is the Microbead-Free Waters Act of 2015 (Public Law 114-114), which bans plastic microbeads in rinse-off personal care products. Broader regulation of MPs and NPs in agriculture, food, and water remains limited, although California requires monitoring and formal definitions for microplastics in drinking water. The European Union has taken a more proactive approach, setting a goal to reduce the presence of MPs in the environment by 30% by 2030 through regulatory actions, while still calling for further study on potential health and environmental effects. Currently, there are no established regulatory limits for MPs or NPs in fresh produce, and public health agencies globally have not yet determined whether existing levels pose a significant health risk. In the US, measures put in place under Food Safety Modernization Act (FSMA) and regulations governing USDA Organic Production indirectly limit introduction of MPs and NPs by putting restrictions on uses of certain soil amendments and management of agricultural water.

MPs have been commonly detected in seafood, meat, honey, and sea salt. We note that retail samples of fresh produce have been very limited, collected from local farmers markets. Data obtained from these samples is difficult to meaningfully interpret as the reported values from independent studies differ by ~100,000 fold. Around the world, plastic particles can be hypothetically introduced into the fresh produce production environment through various routes, including soil amendments, irrigation water, air deposition, and packaging materials. Occurrence and amounts of MPs and NPs in the crop production environment appear to depend on local environmental conditions and production practices, and most well publicized surveys have been carried out in Asia and Europe. Washing produce has been reported to reduce the number of microplastic particles on surfaces.

While field surveys reported the presence of microplastic particles in the field, laboratory studies on the impact of plastic particles on edible plants typically use much smaller nanoparticles (1-1000 nanometer in size). These laboratory reports indicate that under some laboratory conditions, when present in high concentrations in aquatic suspensions, certain nanoparticles can be taken up by plants. However, these studies often use artificially high concentrations or idealized exposure models, or types of plastic particles that are either unlikely to occur in fields or results from plastics that are already being phased out by the industry. Importantly, detecting and measuring MPs and NPs in soil, water, and plant tissue remains technically challenging, with no universally accepted testing standards. As a result, findings from published studies vary widely and should be interpreted with caution.

Human exposure, and regulatory perspectives. Plastic persists and accumulates in the environment due to its durable nature. Once released—whether through improper disposal, surface runoff, or consumer waste—it undergoes degradation processes that break it into small particles known as microplastics (MPs) which can be further fragmented into even smaller particles called nanoplastics (NPs). These particles are mobile, enabling them to travel from their original source, hence increasing their interaction with ecosystems and humans. Wind and stormwater runoff are considered the primary mechanisms for transporting plastics from land to aquatic environments. Additionally, overland flow during precipitation events can carry MPs from land into nearby water bodies (Zhang et al., 2020). Some MPs may even migrate vertically through stormwater infiltration, reaching groundwater systems where they can then be transported downgradient, away from their original source. MPs have even been hypothesized to travel up to 6,000 km, both through air and water but due to the extremely small size of MPs and NPs, tracking their exact movement is challenging (Aves et al., 2022). Key factors influencing travel distance include particle size and shape. Smaller, lighter particles are more likely to travel farther. Water currents and wind—such as ocean and river currents, as well as wind patterns—heavily influence how far MPs travel. Environmental conditions also play a significant role; factors like salinity, water temperature, and the presence of marine life can impact dispersion.

MPs are defined as plastic particles smaller than 5 mm. Nanoplastics (NPs) are even smaller fragments of MPs, generally ranging from 1 to 1,000 nanometers (nm) in size. For perspective, the average width of a human hair is about 80,000–100,000 nm. Due to their small size, NPs are considered to pose greater concerns than MPs. Primary MPs are intentionally manufactured for specific uses, such as preproduction plastic pellets, microbeads in personal care products, and coatings on seeds or fertilizers. Secondary MPs, by contrast, result from the breakdown of larger plastic items, including packaging materials and agricultural mulch. MPs exhibit considerable variation in size, shape (e.g., beads, pellets, fibers, fragments, films), and chemical composition—all factors that influence their environmental behavior and persistence. Importantly, MPs have been detected in every environment studied to date. While secondary MPs are thought to account for the majority of environmental MP pollution, the full extent of their global distribution and impact on ecosystems remains uncertain.

Though MPS are reportedly widespread in the food supply, public health agencies like the WHO and the U.S. Food and Drug Administration (FDA) state that the current evidence is inconclusive and call for more research on exposure and long-term health effects. FDA is clear with its position -- current scientific evidence does not demonstrate levels of MPs or NPs detected in food pose a risk to human health (FDA, 2024). The FDA continues monitoring research findings. Health Canada recognizes MPs as an emerging environmental and public health concern. Similar to the U.S. FDA, Health Canada state that current scientific evidence does not conclusively link MPs and NPs to human health risks. The European Union has adopted the most comprehensive stance through a combination of regulatory measures, research initiatives, and international cooperation. The EU has set a target to reduce MP releases into the environment by 30% by 2030. This goal is part of the Zero Pollution Action Plan and is pursued through various legislative measures and initiatives. While the EU acknowledges the presence of MPs in water, soil, and air, it like the FDA and Health Canada emphasizes the need for further research to fully understand their impact on human health and the environment (European Commision, 2024).

MPs present in the environment can reach humans through three main pathways: inhalation, dermal exposure, and ingestion via food. To our knowledge, only five studies have estimated human dietary intake of MPs (Cox et al., 2019; Senathirajah et al., 2021; Nor et al., 2021; Zhang et al., 2020; Milne et al., 2024). All concluded that existing data are difficult to compare, incomplete, and insufficient for reliable assessment of health risks associated with MP ingestion. Cox et al. (2019) estimated that humans consume between 39,000 and 52,000 MP particles/per year, whereas a more recent U.S. study estimated annual adult intake of a maximum estimated exposure of 3.8 million MPs/year but this latter study only focused on 16 protein sources, however medium or lower limits of potential exposure were not reported by the authors (Milne et al., 2024). In 2022, Plastics Europe launched *Brigid*, an independent five-year research project aimed at assessing the potential human health risks associated with MP ingestion. As part of this initiative, a pilot-scale human intervention study was conducted to examine the relationship between plastic usage scenarios, food consumption, and MP content in human stool (Hartmann, et al., 2024). MPs were detected in 95% of stool samples, with an average concentration of 3.5 MP particles/g of stool. No clear correlation was found between eating plastic-packaged foods or beverages and MP levels in stool. However, these investigators suggested a new hypothesis--a potential link between food processing methods and MP presence in human stool.

MPs have been identified in a number of food items—primarily in seafood (fish and shellfish), table salt, sugar, rice, bread, bottled water, and soft drinks—and can be introduced at various stages including processing, storage, and transportation (Kwon et al., 2020). Alberghini et al. (2022) reviewed nearly 100 studies on MP presence in fish and fishery products, reporting average concentrations of 2.41 to 2.84 MP particles/g wet weight. An analysis of 16 commonly consumed protein products in the U.S.—including seafood, meat, and plant-based alternatives—reported an average MP concentration of 74 ± 220 particles/serving, with contamination ranging from 2 ± 2 particles in chicken breast to 370 ± 580 in breaded shrimp. It is of note that the experimental error values exceed the reported average/median, highlighting the variability of data in the collected samples. Highly processed foods contained significantly more MP particles than minimally processed foods, while no significant differences were observed across brands or store types. Only two studies—Conti et al. (2020) and Aydın et al. (2023)—quantified MP concentrations in fresh fruits and vegetables. Conti et al. (2020) analyzed samples of apples, pears, carrots, broccoli, and lettuce purchased from local markets in Catania, Italy. Mean MP concentrations were: apples (195,500 ± 128,687 particles/g), pears (189,550 ± 105,558 particles/g), carrots (191,950 ± 44,368 particles/g), broccoli (126,150 ± 80,715 particles/g), and lettuce (50,550 ± 25,011 particles/g). The smallest particles were found in carrots (1.51 μm) and the largest in lettuce (2.52 μm). In Turkey, Aydın et al. (2023) reported much lower concentrations that did Conti et al. (2020): tomatoes (3.6 ± 1.4 particles/g), cucumbers (3.6 ± 1.8 particles/g), pears (3.1 ± 1.3 particles/g), apples (3.1 ± 1.2 particles/g), onions (2.6 ± 1.5 particles/g), and potatoes (1.5 ± 1.6 particles/g). Most detected MPs (86.1%) ranged in size from 0.1 μm to 1 mm. For both of these studies, all samples were washed and blended prior to analysis so we are unable to determine if particles were on the surface or internalized. The 100,000-fold differences in the results reported in these samplings from local farmers markets are also difficult to interpret.

Potential sources of MP/NP and prevalence in specialty crop production systems

Although research on the source of MPs in specialty crop systems is expanding, evidence of the effects of MPs and NPs on these systems is limited. This limitation is primarily due to the absence of standardized definitions, reference materials, sampling and preparation protocols, and validated analytical methods that can reliably detect environmentally relevant plastic mixtures under real-world conditions. Foundational to creating a robust body of evidence is access to and application of analytical methods with the capability to quantify and characterize MPs and NPs in complex food matrices. However, the early stages of method development and application of early-stage methods to study the distribution and potential health effects of MPs and NPs in food have largely been done without consideration of the stringent requirements of methods necessary to inform regulatory activities (Duncan et al., 2024).

Airborne Particles. MPs can be transported through the air and deposited onto agricultural fields. Larger particles typically settle near their source, while smaller ones can travel long distances—some as far as 6,000 km (Alves et al., 2022). This transport occurs through atmospheric fallout, where MPs from urban and industrial areas are carried by wind and rain before settling on crops and soil surfaces. A study conducted in China estimated that atmospheric MP deposition varied from 0.91 x 10^3 to 3.5 x 10^3 MP/m^2/day in urban areas (Sun et al., 2022). Concentrations were much lower in remote South Central Appalachia with the average atmospheric MP deposition 68 MPs/m^2/day (Einahas et al., 2024). Concentrations of atmospheric deposition vary widely. The deposition rate may depend on factors such as land use and local climate (Leonard et al., 2024; Carriera et al., 2024).

In general, indoor MP concentrations are higher than those outdoors, although both are considered relatively low overall. MP concentrations in indoor spaces can vary widely—from just a few to several thousand particles per cubic meter—depending on factors, such as the type of space, human activity, and ventilation. A study by Torres-Agulló et al. (2022) measured MP concentrations in three types of indoor environments: homes, public transportation, and workplaces. Public transport showed the highest average levels, with 17.3 ± 2.4 MPs/m³ in buses, followed by 5.8 ± 1.9 MPs/m³ in subways, 4.8 ± 1.6 MPs/m³ in homes, and 4.2 ± 1.6 MPs/m³ in workplaces. Most detected MPs were under 100 μm, with fibers (64 ± 8%) and fragments (78 ± 11%) the most common. Environmental factors, such as carpeting, airflow, and the use of plastic-based personal protective equipment, significantly influence MP levels.

Agricultural Waters. A major source of MPs in agricultural soil is agricultural water, which can become contaminated through multiple pathways, including plastic mulch, irrigation water, stormwater runoff, and atmospheric deposition. A study conducted in Taiwan reported MP concentrations in irrigation water ranged from 1.88 to 141 items/L. The distribution was widespread and uneven along the irrigation system, with highest concentrations near densely populated areas and sites receiving inputs from lateral canals and urban runoff (Jiang et al., 2023). In Tijuana, Mexico, stormwater runoff samples showed a median MP concentration ranging from 66 to 191 particles/L, with the highest levels in areas characterized by industrial land use (Piñon-Colin et al., 2020). Estimated annual MP loads from stormwater ranged between 8 × 10^5 and 3 × 10^6 particles per hectare, with peak loads occurring during heavy rainfall events. Suspended MP concentrations in urban air have been reported at levels between approximately 1 and 35 particles/m^3 (Xu et al., 2022). In a remote mountain catchment, rainfall showed moderate to significant correlations with MP deposition fluxes (Allen et al., 2019). Conversely, a study in urban areas by Klein et al. (2019) found no significant correlation between MP deposition and precipitation, but rather a stronger association with wind speed. However, earlier research in Paris indicated rain events may enhance MP deposition in urban environments (Dris et al., 2015). The average range of MP concentrations in agricultural waters is highly variable, often spanning several orders of magnitude. This variability is influenced by multiple factors, including agricultural practices, the effectiveness of wastewater treatment, climate conditions, and atmospheric deposition. It is important to note further that at the time of writing of this report, no peer-reviewed studies reported presence of MPs or NPs in agricultural waters actually used for irrigation in the United States. We further note that the Ag Water Rule within FSMA, while not designed to deal with the presence of MPs or NPs, would limit introduction of these particles into pre-harvest ag waters by already mandating limiting the introduction of urban run-off into specialty crop production systems, and putting restrictions on the use of surface waters in general.

Soils. Soil is a major sink for MPs, acting as a direct pathway for entry into the food chain (Allen et al., 2022). Agricultural fields are sources of MPs for two main reasons. MPs found in soil can hypothetically be re-emitted to the atmosphere from soils undergoing wind erosion. Wind erosion and drought are interconnected natural processes that significantly impact soil health, agriculture, and ecosystems, especially in arid and semi-arid regions. Published studies report the effect MPs have on soil crusting, surface sealing, and reduced aggregate stability, making the impacted soil more susceptible to wind erosion and dust uplift (Zhang, et al., 2023). A review by Sa'adu and Farsang (2023) identified both primary and secondary sources of plastic in agricultural soils and described mechanisms through which these particles enter the soil ecosystem. The majority of studies on this topic were conducted in Asia (60%), followed by Europe (29%), Africa (4%), North America (4%), and Latin America (3%) with no studies from Australia. Microplastic concentrations in soils in the vicinity of municipal areas were 10 times larger compared to rural sites. Data was collected from China, Europe, the Americas, Middle East, and Australia (Büks and Kaupenjohann, 2020).

Primary sources include the unintentional release associated with the use of controlled-release fertilizers. Secondary sources result from the physical weathering and fragmentation of larger plastic debris—such as plastic mulch and greenhouse films—under environmental stressors like sunlight and wind. Biosolids from wastewater treatment plants were also highlighted as a contributor, with MPs detected in treated effluents. Study region significantly impacts MP dispersion. Regions with high population density, industrial activity, and proximity to rivers or estuaries tend to have higher concentrations. Ocean currents, weather patterns, waste management practices, as well as human-driven behaviors also influence how MPs are dispersed and accumulate in different regions. MPs were found across a wide range of soil types, including arable land, paddy fields, uplands, irrigation zones, and greenhouse farmlands. Of the 20 studies reporting MP concentrations, most showed no significant variation across regions or soil types. However, three studies stood out due to particularly high concentrations of MPs: one conducted in China found 8,885 and 2,899 MP particles/kg^{-1} in soils used for growing maize (Li et al., 2022), while another study conducted in both Spain and the Netherlands reported 2,224 ± 984 and 8,888 ± 500 MP particles/k^{-1} in mixed soils used to grow broccoli, celery, and watermelon (Schothorst et al., 2021). A British study reported similarly high levels of MPs (Cusworth et al., 2023) in all soil samples, with concentrations ranging from 1,320 to 8,190 particles per kilogram. Across 108 sites under various conditions, the mean concentration was 3,680 ± 129.1 particles/kg. In fields without plastic crop covers (n = 54), the average concentration was 2,667 ± 84.1 particles/kg, compared to 4,689 ± 147.1 particles/kg in fields where plastic covers were used (n = 54). This difference was statistically significant ($p \leq 0.001$), with microplastic concentrations being 175.8% higher in soils where plastic crop covers were applied. Büks and Kaupenjohann (2020) reported microplastic contents in plastic-mulched agricultural soil ranging from 0.1 to 1.2 mg kg^{-1}. The majority of the sites were also exposed to biosolids and mulching film application and showed concentrations of < 13, 000 particles/kg^{-1} dry soil and 4.5mg/kg^{-1} dry soil. Given disparity in the number of studies conducted in different geographies and significant differences in common horticultural practices in these regions, much care should be taken when extrapolating results of studies to other regions, especially of the much-cited studies reporting outlier results.

Plastic Mulch. Plastic mulch fragments into smaller pieces over time due to environmental exposure (e.g., UV radiation, wind, and rain) and mechanical actions, such as tilling and cutting (Falconi et al., 2024; Quilliam et al., 2023; Sa'adu and Farsang, 2023). Mulch plastics—primarily polyethylene (PE)—account for approximately 50% by weight of all agricultural plastics (Hofmann et al., 2023). Agricultural soils can become overloaded with secondary MPs due to frequent tillage, which incorporates plastic debris into soil mineral aggregates (Steinmetz et al., 2022). Plastic mulch, which cover approximately 20 million hectares globally—with China accounting for 90% of usage—gradually degrade and release MPs. Perhaps not surprising, most studies on the consequence of this usage are from China, with no surveys in the US or Canada currently available. Li et al. (2022) analyzed MPs after 32 years of continuous plastic mulch application at Shenyang Agricultural University in China. In the topsoil (0–10 cm), MP concentrations increased from 7,183 to 10,586 particles/kg, with an average of 8,885 particles/kg. In the subsoil (80–100 cm), levels increased from 2,268 to 3,529 particles/kg, averaging 2,899 particles/kg. Similarly, Wang et al. (2021) reported MP abundances ranging from 2,783 to 6,366 particles/kg in farmlands across five Chinese provinces, with over 80% of particles measuring under 1 mm. The most common MP size range was 0.02–0.2 mm. Huang et al. (2020), in a study across 19 Chinese provinces, found higher MP concentrations in fields subjected to long-term plastic mulching. Soils mulched for 5, 15, and 24 years contained 31–129.6, 169–446.1, and 728–1,422.4 particles/kg, respectively. While no surveys are available in the US or Canada, in the countries with Western-style agriculture, reported prevalence of MPs and NPs in soils is much lower. For example, a study conducted in Germany reported lower concentrations in fields using mulch films for 12 years (Steinmetz and Schröder, 2022). Microplastic PE levels ranged from 0.03 to 0.55 mg kg^{-1} across all sites hardly exceeding the method limit of detection of 0.40 mg kg^{-1}, even though MP concentrations detected in fields with mulch film management were considerably higher than in the respective controls. However, even the maximum values of 0.55 mg kg^{-1} PE and 1.2 mg kg^{-1} PP were close to the method limit of detection, which makes it hard to draw definite conclusions. Similarly, a meta-analysis of 23 studies by Büks and Kaupenjohann (2020) reported microplastic contents in plastic-mulched agricultural soil ranging from 0.1 to 1.2 mg kg^{-1}. The majority of the sites were also exposed to biosolids and mulching film application and showed concentrations of < 13, 000 particles/kg^{-1} dry soil and 4.5mg/kg^{-1} dry soil.

Biosolids. Under the Food Safety Modernization Act (FSMA), the use of biosolids—treated sewage sludge from human waste—is tightly regulated in fresh fruit and vegetable cultivation. While biosolids are not classified as Biological Soil Amendments of Animal Origin (BSAAO) under the Produce Safety Rule (PSR), their use is still limited. According to 21 CFR 112.53, human waste can only be used if it has been treated in compliance with EPA's biosolids regulations (40 CFR Part 503) and applied in a manner that prevents any contact with covered produce during or after application and avoids contamination throughout the growing and harvesting process. Even if biosolids meet EPA standards for pathogen and vector reduction, as well as limits on heavy metals, their use remains limited in the United States. FSMA does not endorse or recommend the use of biosolids, and the responsibility lies with the grower to prove that their use poses no risk of contamination. As a result, most produce growers do not use biosolids and instead rely on more broadly accepted alternatives, such as composted animal manure or treated poultry litter. These alternatives, when used in compliance with FSMA microbial standards and required application intervals, align better with Good Agricultural Practices (GAPs) and third-party certification programs. Use of sewage sludge is specifically disallowed in Title 7, Subpart C (Organic Production and Handling Requirements) § 205.203. Outside of the US, biosolids are globally used as a soil amendment and fertilizer with the Asia Pacific region dominating the biosolids market with a share of 35%. Global studies have shown that the primary factor restricting the agricultural use of biosolids is its contamination with heavy metals (Ajibola and Zwiener, 2022; Siebielec et al., 2018; Urbaniak et al., 2017).

The application of biosolids to agricultural fields is particularly common in Asia (Wang et al., 2021). Because ~98% of the MPs in wastewater are retained in biosolids (Amaral-Zettler et al., 2025), the application of biosolids to agricultural fields represents an important pathway for MPs to enter the environment. In addition, plastic mulch is often added to soils to increase temperatures while retaining moisture, serving as another potential source of MPs (Wang et al., 2021). Applying biosolids to agricultural land has created a large global reservoir of MPs in soil in those regions and production systems where the applications of biosolids is routine(Lofty et al., 2022). Biosolids, commonly used as fertilizer, contain high MP concentrations. For example, biosolids used for agricultural purposes in Chile was found to contain up to 41,000 particles/kg (Corradini et al., 2019). Comparative studies show MP concentrations were 2.3-2.8 times higher on soils amended with biosolids compared to untreated soils (van den Berg et al., 2020). Where used, biosolids have been reported to introduce an estimated $7.2\ 10^{12}$ to $1.5\ 10^{14}$ MP particles/year to agricultural fields (Iyare et al., 2020), with concentrations generally increasing with the number of applications (van den Berg et al,. 2020; Schell et al., 2022; Tagg et al., 2022; Crossman et al., 2020). An empirical study conducted in Ontario, Canada, reported MP concentrations in biosolids ranged from 8.7×10^3 to 1.4×10^4 particles/kg (Crossman et al., 2020) whereas two European studies reported much lower concentrations. A study in Spain reported 10–30 particles/g, with particle diameters ranging from 0.5 to 30 mm (Edo et al., 2022) and a German study reported a 46 ± 8 particles/kg, with an average particle size greater than 5 mm (Braun et al., 2021). Regional variations in the concentration and types of MPs in biosolids exist, influenced by factors like wastewater sources and treatment processes.

MPs enter raw wastewater that is then carried to a wastewater treatment plant (WWTP). While conventional WWTP removes a large portion of MPs, they do not filter out all sizes, particularly NPs. Once MPs enter the WWTP, the majority accumulates in the sludge fraction, while a much smaller fraction is released into the environment through discharge water (Ziajahromi et al., 2016). MPs are primarily removed from the water phase during settling of the solid phase in a series of connected settling tanks (Zhang et al., 2022; Gao et al., 202). One study assessing distribution of MPs within a Swedish WWTP found that 66% of the smaller MP particles (500 µm) were within the sludge fraction (Rasmussen et al., 2021). In a comparable study, 84% of the MPs entering the WWTP were removed from the effluent, meaning MPs were instead enriched in the solid sludge fraction with concentrations of 113 ± 57 MP particles/g^{1} dry weight (Magni et al., 2018). Another study from a Spanish WWTP found similar concentrations in the sludge fraction with 165 ± 37 MP particles/g^{1} dry weight (Edo et al., 2020). In contrast, a study from Taiwan reported markedly lower concentrations of 1 and 7 MP particles/g^{1} in sludge (Wang, et al., 2022) suggesting regional differences might influence the MP distribution within WWTPs.

Specific treatment methods also affect MP concentrations. Rapid sand filtration was shown to physically remove 70–97% of MPs (Bayo et al., 2020a; Hidayaturrahman and Lee, 2019; Ngo et al., 2019) and membrane disc filters removed up to 80% of treated MPs. Chlorination also was reported to remove 20–68% of the remaining MPs (Galafassi et al., 2022; Ngo et al., 2019). Ozone has a similar effect resulting in almost 90% of MP degradation in 1 min of contact time (Hidayaturrahman and Lee, 2019). UV showed the lowest effectiveness (≤10 %) (Galafassi et al., 2022). Thickening and dewatering have also been reported to remove up to 6% and 54% of MPs from sludge flux, respectively (Petroody et al., 2021).

Various treatment methods, such as rapid sand filtration, membrane disc filters, chlorination, ozone, and UV, have differing levels of effectiveness in removing MPs, with ozone achieving up to 90% degradation and UV showing the least (<10%). MPs in biosolids can pose environmental risks by altering soil properties, migrating into groundwater, and adsorbing harmful substances like heavy metals and antimicrobials, which can contribute to antimicrobial resistance and limit the agricultural use of biosolids. Applying biosolids to agricultural land can introduce large quantities of MPs into soils, with studies reporting concentrations as high as 41,000 particles/kg and biosolid-amended soils containing 2.3–2.8 times more MPs than untreated soils. Most MPs in wastewater are removed during treatment and accumulate in the sludge, which is later used as fertilizer, with removal efficiencies and MP concentrations varying widely by region and treatment method. Treatment technologies, such as sand filtration, membrane filtration, and ozone application, can significantly reduce MP concentrations, though some methods like UV are less effective. Even though biosolids are not used in the US for commercial fruit and vegetable production, it appears that the waste treatment methods, particularly those used in the sewage treatment in the West are capable of significantly reducing presence of plastic particles in biosolids.

Food Waste. Food waste can be incorporated into biosolids used under the Food Safety Modernization Act (FSMA), if specific regulations and requirements are met. FSMA permits the use of sewage sludge biosolids that have been treated in accordance with EPA standards, which may include biosolids derived from processed food waste. However, the use of untreated food waste is prohibited for the cultivation of covered produce. Please see comments on biosolids use above. Compost derived from food waste can serve as a source of MPs, especially when household and industrial wastes are included in composting streams (Porterfield et al., 2023). It is of note that the presence of plastics, including compostable plastics is not specifically allowed in compost for organic production in the US per § 205.601 (Synthetic substances allowed for use in organic crop production).

The concentration of MPs in food waste has shown extreme variability, spanning five orders of magnitude on a count-per-weight basis across three studies (Porterfield et al., 2023). For example, Ruggero et al. (2021) reported concentrations of 1,400 ± 150 particles/kg dry weight in food waste in Italy, where the analysis was limited to larger particles (1–5 mm). In contrast, a German study by Schwinghammer et al. (2020), which focused on smaller particles (0.1–2 mm), found a much lower concentration of 36 particles/kg dry weight. Meanwhile, a U.S. study of grocery waste detected 300,000 particles/kg dry weight, though it did not provide information on particle size (Golwala et al., 2021). On a mass basis, the abundance of plastic in food waste has also varied widely—from approximately 0.025% w/w in homogenized food waste (Schwinghammer et al., 2020) to as high as 5.6% w/w in source-separated household biowaste (do Carmo Precci Lopes et al., 2019).

Controlled-Release Fertilizers (CRFs). Controlled-release fertilizers (CRFs) are designed to release nutrients gradually, thereby enhancing fertilizer efficiency and crop productivity. CRFs typically use polymer coatings made from thermoplastic resins, such as polyolefin, polyvinylidene chloride, and copolymers. However, these materials are not readily biodegradable and can persist in soil, leading to long-term environmental accumulation (Surendran et al., 2023). As the polymer coatings degrade over time, they can release MPs into the soil. These MPs may undergo further mechanical fragmentation, producing even smaller particles (Bhattacharjee et al., 2025). Studies have shown that surface wear and compression forces on CRFs can generate MPs, with longer wear durations increasing particle quantity and higher loads resulting in larger particle sizes. While CRFs provide clear agronomic benefits, these environmental concerns have prompted regulatory action in some regions of the world. CRFs are widely used around the world, with the United States, Canada, and Mexico serving as large markets, but their use is being restricted in the European Union. The European Commission recently acknowledged the link between fossil-based polymer fertilizers and MPS, having introduced regulations that will ban non-biodegradable polymer coatings over a five-year transition period. Beginning in 2026, only CRFs with coatings that meet biodegradability standards will be allowed on the EU market.

Organic production. The use of plastic is largely unavoidable in organic agriculture, where plastic mulch, seed-starting pots, and plastic coatings on fertilizers and seeds are commonly used. MPs have been detected in organic fertilizers across several countries--China, Bangladesh, and Mexico. We note, however, that the Chinese Organic Program, while structurally similar to the USDA Organic is not considered “equivalent”; Bangladesh does not have a government-run organic program and producers use requirements of the destination markets; organic standards for fresh produce are substantially similar in the US and Mexico, and a bilateral equivalency agreement is in place.

Zhang et al. (2022) analyzed 102 organic fertilizer samples collected from 22 provinces in China. MP concentrations ranged from undetectable to 2,550 particles/kg, with an average of 325 ± 511 particles/kg and a detection frequency of 80.4%. The highest average concentrations were in Beijing (758 particles/kg) and in compound organic fertilizers (386 particles/kg). Over half of MPs were 1–3 mm in size (55%). Additionally, MP concentrations were higher in provinces with intensive agricultural activities. Similarly, Zhang et al. (2023) tested 124 samples of organic composts, including single-feedstock types (livestock manure, poultry manure, crop straw, and solid waste) and compound composts. MP concentrations were highest in compost from solid waste (6,615 particles/kg^{-1}) and lowest in crop straw (1,500 particles/kg^{-1}). Most MPs (39.5%) in these samples were 0.5–1 mm. In Bangladesh, a study of 18 organic fertilizer samples sourced from local markets reported average concentrations of 1,529.62 ± 420.2 particles/kg, ranging from 433.33 ± 152.75 to 3,466.67 ± 1,357.69 particles/kg (Rana et al., 2023). The dominant size was 0.5–1.0 mm (30%). Further evidence of MP presence has been found in animal manures. For example, Lwanga et al. (2017) detected 129.8 ± 82.3 items/kg in chicken feces in Mexico, mainly in the 0.1–1 mm size range. Yang et al. (2021) reported concentrations of 1,250 ± 640 particles/kg, with sizes ranging from <0.5 to 5 mm, in pig manure. Plastic use is prevalent in organic agriculture, and MPs have been widely detected in organic fertilizers and composts across countries like China, Bangladesh, and Mexico, with concentrations varying by region, feedstock, and agricultural intensity. Studies have found MP levels ranging from undetectable to over 6,000 particles/kg, with most particles measuring between 0.5–3 mm and higher levels often linked to solid waste-based composts and intensive farming areas. At the time of writing of this document, no results of peer-reviewed surveys of composts in the US or in Canada were available. It is important to point out that USDA NOP 5021 Guidance

Compost and Vermicompost in Organic Crop Production Compost containing plant and animal materials § 205.203(c)(2) and § 205.601 (Synthetic substances allowed for use in organic crop production) do not specifically allow inclusion of plastics, including compostable plastics into organic compost. The inclusion of sewage sludge in organic compost is also specifically prohibited in § 205.203 (Soil fertility and crop nutrient management practice standard).

Prevalence in Greenhouse Production: Chia et al (2022) examined the abundance and distribution of MPs in greenhouses and mulched soils of Korean agriculture fields. In their study, the MP concentrations in the greenhouse and mulched soils ranged from 50 to 379 and 158 to 943 particles/ kg^{-1}, respectively, with an average concentration of 221.4 and 356.8 particles/kg^{-1}. MPs with a size < 300 μm were most common. Sa'adu and Farsang (2022) collected composite samples from shallow (0–20 cm) and deep (20–40 cm) soils from a greenhouse farm in Hungary. The average MP concentration in the greenhouse soil was 225 ± 61.69 particles/kg, and the common size was 2–3 mm. The average MP concentrations at depths of 0–20 and 20–40 cm were 300 ± 93 particles/kg and 150.0 ± 76.3 particles/kg, respectively. Wang et al. (2022) tested for MP presence in three types of greenhouses (abandoned greenhouse, "normal" greenhouse, and "simple" greenhouse) in China. MP concentrations were highest in abandoned greenhouses (2215.56 ± 1549.86 particles/kg^{-1}) followed by "normal" greenhouse (891.11 ± 316.71 particles/kg^{-1}) then "simple" greenhouse (632.50 ± 566.93 particles/kg^{-1}). MP concentrations in shallow soils of the abandoned greenhouse (826.67 ± 261.02 particles/kg^{-1}) and "normal" greenhouse (560.00 ± 52.92 particles/kg^{-1}) were lower than those in the deep soils (1073.33 ± 306.16 particles/kg^{-1} and 720.00 ± 111.36 particles/kg^{-1}), while the "simple" greenhouse showed the opposite result. Average MP size was 0-1 mm. Microplastic concentrations in greenhouse soils vary widely depending on location, greenhouse type, and soil depth, with abandoned greenhouses showing the highest levels. Studies report MP sizes mostly under 3 mm, often smaller than 1 mm, and concentrations ranging from around 50 to over 2,000 particles per kilogram of soil. Additionally, mulched open-field soils can sometimes have higher MP concentrations than greenhouse soils, and MPs have even been detected in groundwater beneath greenhouses. MP levels in greenhouse soils vary widely by location, greenhouse type, and depth, with abandoned greenhouses generally showing the highest concentrations—up to over 2,000 particles/kg—while sizes are mostly below 3 mm. Studies have also detected MPs in groundwater beneath greenhouses, highlighting potential environmental risks.

Evidence of root uptake by model plants and crops

It should be noted that the studies above focused on the surveys of microplastics (MP) in various environments. Researchers hypothesize that once in the soil, MPs can become further fragmented into NPs. NPs range in size from 1 to 1,000 nm and hypothesized to more likely than MPs (approximately 1000X larger than NPs) penetrate root tissues then translocated to aboveground plant parts (i.e., stems, leaves, flowers, and fruits) (Vitali et al., 2023; Bandmann et al., 2012). However, studies on the prevalence of nanoplastics in the crop production environment are limited. Due to their size and charge they interact and get retained by other charged soil particles (clay, silt), as well charged surfaces of soil microorganisms. Therefore, laboratory studies on the update of nanoplastics should be appropriately contextualized, as suspensions of nanoplastics in aqueous solutions do not mimic native soil conditions, nor the complexities of interactions within soils, soil microbes (and their secretions) and secretions from plant roots.

Under laboratory conditions, the uptake of MPs by plant roots is influenced by particle size, surface charge, and presence of root exudates (Nath et al., 2024). Parkinson et al. (2022) demonstrated uptake into roots and protoplasts of *Arabidopsis thaliana* (thale cress). Uptake was inversely proportional to nanoparticle size, which in this study ranged from 20 to 100 nm. Larger nanoparticles were detected only in the shedding lateral root cap cells and in the occasional epidermal cells in the root hair zone. For context: most plastic particles detected and reported in soils are at least 10-100x times larger in size than the those that were retained in epidermis and on root surfaces. Another important outcome of the Parkinson et al (2022) study is that positively charged plastic nanoparticles accumulated at root surfaces and were *not* taken up by roots or protoplasts. Polyethylene, typically used for plastic mulches in crop production, is positively charged at pH above 2.5 (which represents all agricultural soils), and therefore its uptake into roots is unlikely. Negatively charged nanoparticles accumulated slowly and became prominent over time in the xylem of intact roots, while neutral nanoparticles penetrated rapidly into intact cells at the surface of plant roots and into protoplasts, but xylem loading was lower than for negative nanoparticles. Similarly, Sahai et al. (2024) demonstrated uptake and bioaccumulation of 100 nm polystyrene (typically having a negative or a neutral charge) NPs in the roots, stems, and leaves of *Lepidium sativum* (watercress), reporting 13-18% of NPs were transferred to aerial parts compared to median root accumulation. The accumulation of NPs in root, stem, and leaves was directly proportional to exposure concentration. However, no clear difference was observed between the accumulated amount in stem and leaves of the plant. Effects were only significant at exposure concentrations at and above 50 mg/L, which were highly unlikely in the natural environment. Lower exposure concentrations of 10 µg/L, 100 µg/L, and 1 mg/L did not significantly affect plant health. In contrast, other research has found no evidence of MP uptake in plants. For example, a laboratory-controlled study conducted by Taylor et al. (2020) showed no internalization of 40 nm and 1 µm polystyrene spheres in the roots of *Arabidopsis* and wheat, although particles did accumulate on the root surface. The inconsistency across studies highlight the complexity of uptake pathways and illustrates the need for more research to clarify the environmental and physiological conditions leading to root uptake. It is of note that the use of polystyrene (Styrofoam) is already being phased out in 6 US states (ME, MD, NJ, VT, CO, and WA), and CA, DE, OR, and RI will begin the phase out after 2025. Canada amended its 'Canadian Environmental Protection Act, 1999' in 2022 to prohibit use of expanded or extruded polystyrene in foodservice. In Australia, over 97% of the population live in an area that bans expanded polystyrene. Similar efforts are underway in the EU, and elsewhere.

An important limitation of all three studies (Parkinson et al., 2022; Sahai et al., 2024; and Taylor et al., 2020) is that all were conducted using growth media rather than soil, under controlled laboratory conditions. All three studies used plastic nanoparticles, however, it is important to highlight that the vast majority of soil surveys focused on the presence of much larger micro-sized particles, that are even less likely to be able to enter roots and be taken up by them. While researchers often draw a direct line between the presence of microplastics in soils and the hypothetical presence of nanoplastics, it was not demonstrated experimentally, nor was the bioavailability of plastic nanoplastics for root uptake. Study results also show that NP uptake depends on factors like particle size, surface charge, and root exudates, with negatively charged and smaller NPs showing greater accumulation in plant tissues. However, inconsistencies in findings—such as Taylor et al. (2020) showing no internalization—highlight the complexity of NP uptake and emphasize the need for research under real-world soil conditions rather than controlled laboratory environments.

Evidence of presence in packaging and the likelihood of transfer from packaging to the finished product

Plastic packaging—including shopping bags, films, bottles, and foam—can fragment into MPs during common handling activities such as tearing, cutting, or twisting (Sobhani et al., 2020). These seemingly minor actions can release between 0.46 and 250 MP particles per centimeter, depending on characteristics like material stiffness, thickness, anisotropy, density, and particle size. The presence of MPs in food-related plastic products has been documented in several studies. For instance, Du et al. (2020) detected 1 to 41 MP particles per container in newly manufactured take-out packaging in China. Similarly, Fadare et al. (2020) analyzed a range of plastic food containers and disposable cups used in everyday settings. They found that the average MP content per item was 12 ± 5.12 mg for round containers, 38 ± 5.29 mg for rectangular containers, and 3 ± 1.13 mg for disposable cups.

Over time, plastic packaging exposed to environmental conditions—such as sunlight, temperature fluctuations, and moisture—can degrade, producing MPs that may contaminate food (Hahladakis, 2018). Weathering alters both physical and chemical properties of plastics, leading to discoloration, surface erosion, and fragmentation. The extent and rate of degradation depend on factors such as plastic type, environmental conditions, and exposure duration. For example, aliphatic polymers like polyethylene and polypropylene degrade more readily under UV radiation than aromatic polymers such as polycarbonate and polyesters (Pickett, 2018). Environmental stressors—including UV light, heat, humidity, water, and oxygen—further accelerate this breakdown.

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